# INFRASTRUCTURE ISSUES REGARDING THE ULTRAFAST CHARGING OF ELECTRIC VEHICLES

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## Abstract

This paper is devoted to the infrastructure issues arising from the ultrafast charging of electric vehicles in the timeframe of ~5 minutes. To mitigate variances and peaks caused by high energy transfer rate and pulse-like load, an ultrafast charging station must be partially decoupled from the utility grid by the usage of intermediate energy buffers. The perspective charging station load and its management by intermediate buffering are analysed and discussed with a tentative design proposal.

## Introduction

The state-of-the-art electric vehicle (EV) charging is limited to the rated current and voltage of conventional household sockets. For continental Europe, where 230 V/400 V phase-to-neutral and phase-to-phase voltages are used with 16 A sockets as standard, recharging an average EV battery takes at least 6 hours from one-phase connection and 2.5 hours if a three-phase connection is available[1]. There exists already a quick-charging method promoted by the CHAdeMO consortium, allowing recharging an EV battery to 80 % of its rated capacity within 20…30 minutes and based on the IEC 61851-23 standard[2,3] On a highway, this yields driving/charging time ratio in the range of 3:1, which is far away from making EV a serious alternative for long distance driving.

Transferring energy to an electric vehicle traction battery in as short timeframe as possible requires high power, determined not only by the battery's capacity and charging time, but also by the inherent losses due to the electrochemistry. From the grid operator's viewpoint such peaks are undesirable, because they necessitate overdimensioning of cables, power transformers, protection devices etc. The situation becomes even more aggravated if multiple vehicles are charging simultaneously, which brings along the need for a medium voltage connection[4].

A possibility to alleviate the grid impact of the ultrafast charging lies in decoupling load from the grid. This can be done with the implementation of energy storage elements, which act as a buffer between the grid and the charging terminal[5]. A similar approach has been recently implemented in the fast charge of compressed air propelled vehicles[6]. Several energy storage media are further evaluated in terms of performance and costs and an optimal solution proposed.

Finally, a buffered ultrafast EV charging station structure is proposed. Such a station is composed of several modules, comprising in connection ports for the utility grid, EV, storage medium and a common power bus. The modular architecture ensures extensibility if the station's utilisation grows, i.e. the EV market share increases.

To point out the necessity of deepened research in the selected field, available charging methods should be described based on the state-of-the-art and market analysis. The IEC 60851 standard, applicable for conductive charging systems, defines four charging modes, as given in Table 1.

Table 1. Charging modes according to IEC 61851-1, 230 V / 400 V voltage system[7]

| Mode | Max current per phase | Max charging power per phase | Charger location |
|---|---|---|---|
| 1 | 16 A | 3.6 kW | On-board |
| 2 | 32 A | 7.3 kW | |
| 3 | 63 A | 14.7 kW | |
| 4 | dc 400 A | dc 150 kW | Off-board |

However, a discrepancy between the above mentioned standard and market situation exists. Usually the EV manufacturers prefer to sell their products in set with a Mode 1 one-phase on-board charger; as standard household 16 A sockets are used, de-rated to 10 A … 12 A at constant load, the charging power is even more limited, to 2.3 kW … 2.8 kW. Thus a small-sized EV with a 16 kW·h traction battery would need at least 6 hours to fully recharge.

The Mode 4 utilising off-board chargers has been implemented by the CHAdeMO consortium[8]. As for today, the charging current is limited to 120 A by the used connector, which enables to recharge a commercial EV within 20 min … 30 min depending on the battery capacity. As for Mode 3, the manufacturers have not reached an agreement on the standard connector, the increased charging rate is achieved by reversing the power flow in the traction inverter and using motor windings as smoothing reactors, thus the charging power can be nearly equal to the rated driveline power. A comparison between commercially available charging methods is given in Table 2.

Table 2. Commercially available EV charging methods

| Charging type | Mode | Min charging time | Autonomy flowrate |
|---|---|---|---|
| Domestic one-phase charging | 1 | 6 h … 8 h | 0.3 km / min |
| Three-phase semi-quick charging | 3 | 20 min … 30 min | 4 km / min |
| CHAdeMO semi-quick charging | 4 | | |
| Diesel tanking for a family car | N/A | 1 min 30 s | 600 km / min |

To make an EV attractive for distances beyond single charging autonomy, an optimal relationship between the battery capacity and autonomy flowrate is the key objective: to increase the average speed, there must be less charging stops and shorter charging times. The transfer of the same amount of energy, in turn, means higher charging power with increased requirements both for the EV battery system and the utility grid connection.

## Materials and Methods

To estimate the load curve of a perspective ultrafast EV charging station, its frequentation must be determined at first. As there are no data on real stations available, analogies may be drawn with conventional fuel stations or other relevant existing statistics applied. It may be assumed, that the frequentation of an ultrafast EV charging station is distributed in time similarly to traffic density, the latter statistics is provided in Switzerland by the Federal Office of Statistics[9]. In Fig. 1, the typical hourly traffic densities are given for highway (counting point near Yverdon) and urban conditions (Chauderon in Lausanne). For charging station load profile generation, averaged urban-extra urban distribution is selected. It should be mentioned, that the frequentation distribution is close to the overall energy consumption distribution with daytime maximums and nighttime minimums.

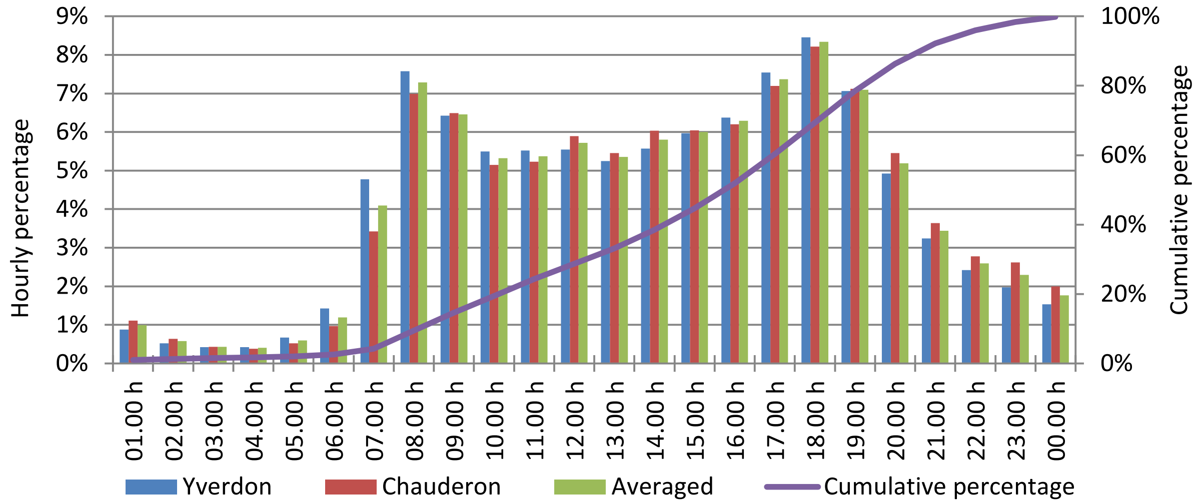


Fig. 1. Typical daily traffic density distributions

The actual load curve, imposed to the utility grid by the ultrafast EV charging depends on the following parameters:

1) objective charging time: taken equal to 5 minutes;
2) EV battery capacity ($E_{bat}$): ranging from 16 kW·h for small vehicles to 55 kW·h for sport cars;
3) initial battery state-of-charge ($SoC_i$), ranging from 0 % to 50 %;
4) EV arrival times to the station, subjected to hourly distribution and daily frequentation.

In following calculations, the $E_{bat}$ values are subjected to left-truncated normal distribution (Fig. 2) based on market analysis and $SoC_i$ to normal distribution (Fig. 3).

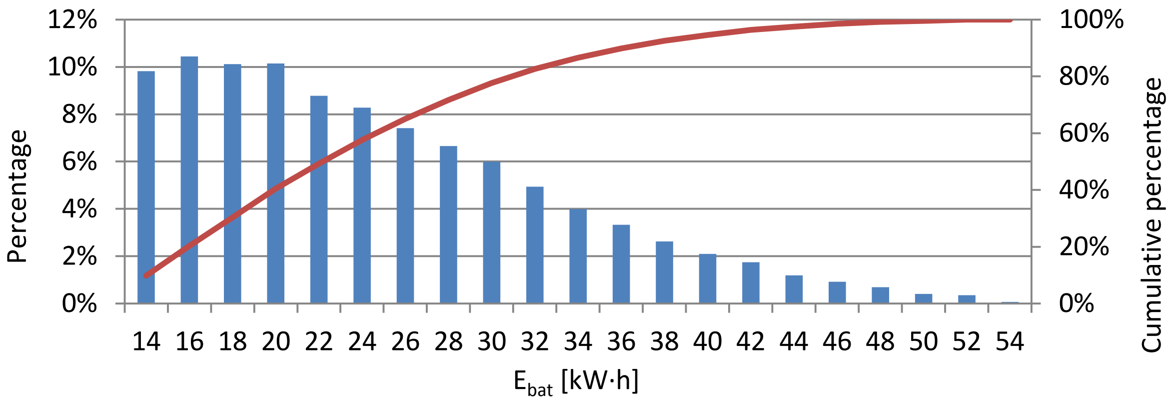


Fig. 2. Presumed EV battery capacity ($E_{bat}$) distribution

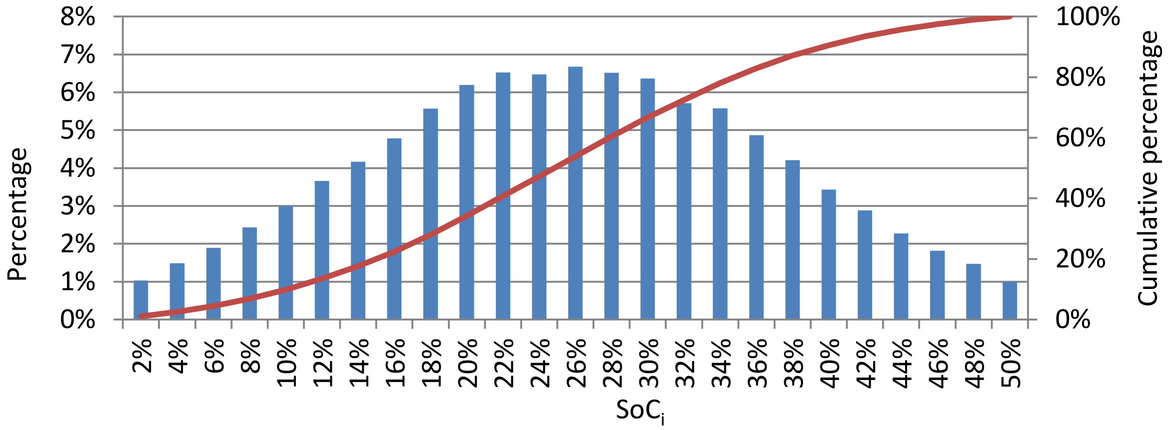


Fig. 3. Presumed battery initial state-of-charge ($SoC_i$) distribution

The load curve simulations are carried out for three frequentation cases: 50 EV/day, 100 EV/day and 200 EV/day. It is further assumed, that an EV can arrive at a charging station in any minute of the given hour, depending on the frequentation and daily distribution (Fig. 1). As the vehicles show variable $E_{bat}$ and $SoC_i$ values, stochastic approach on Monte Carlo method with 10'000 iterations is utilised; the same method already been proposed by some authors[5,10]. As the objective charging time was fixed to 5 minutes, the instantaneous charging power varies according to the transferred energy, defined by $E_{bat}$, $SoC_i$ and inherent losses. The Monte Carlo simulation returns following statistics:

1) instantaneous charging power: median, 3$^{rd}$ quartile and maximum values;
2) daily transferred energy: median, 3$^{rd}$ quartile and maximum values;
3) number of simultaneously charging vehicles: 3$^{rd}$ quartile and maximum values.

As it is known from the descriptive statistics theory, the median value represents the middle of a data set, of which 50 % are smaller and 50 % greater. The 3$^{rd}$ quartile (further referred to as 3Q), in turn, refers to a value of which 75 % are smaller and 25 % greater in a studied data set. So, the median is valid for 50 % of the modelled cases and the 3$^{rd}$ quartile to 75 %. Further, to suppress unwanted peaks in the utility grid, an energy storage buffer must be installed for power flow management. Here, two main partial decoupling strategies are observed:

1) load levelling – an ultrafast EV charging station is supposed to draw moving average charging power from the grid, the average is in the studied case taken over an hour and the strategy itself is based on the discrete low-pass filter analogy;
2) load shifting – to an ultrafast EV charging station, more power is allocated during nighttime and less power during the grid peak hours, so the buffer absorbs energy when the grid overall load is minimal and releases energy for EV charging when the grid is more heavily loaded.

A buffered EV charging station can be described as a three port entity with connection ports for the utility grid, electric vehicle and energy storage buffer (Fig. 4). This general conception is based upon the dc architecture with a common dc bus and each port characterised by power $P_{gr}$, $P_{EV}$, $P_{st}$ as well as energy conversion and transmission efficiency $\eta_{gr}$, $\eta_{EV}$, $\eta_{st}$, respectively.

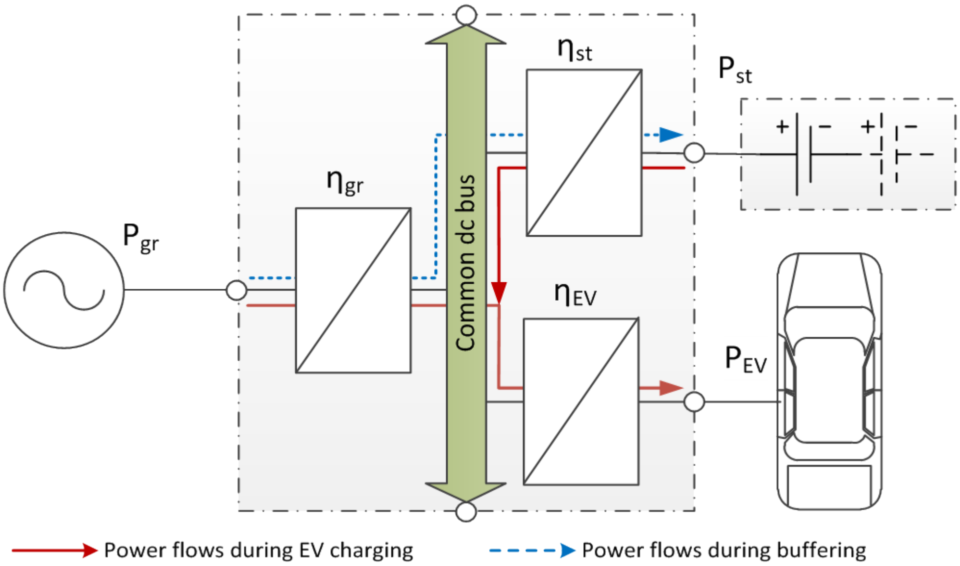


Fig. 4. Power flows in a buffered EV charging station

After buffer power and capacity calculations, suitable storage technologies are compared side by side with following main selection criteria:

1) energy density – energy stored in a volume unit;
2) power density – medium-term (5 min … 30 min) power absorbed and delivered by a volume unit;
3) cyclic lifetime;
4) investment cost per energy unit;
5) investment cost per power unit.

Alongside with buffering, considered as a hardware-based “hard” power flow management method, the so-called “soft” methods based on load-side management, i.e. charging power limitation and vehicle scheduling can be applied for cost and complexity optimisation. Though the initial objective was to shorten the EV battery charging time to 5 minutes, keeping this value for every $E_{bat}$ and $SoC_i$ combination would not obviously be feasible for a 55 kW·h fully depleted sports car battery. Furthermore, the Monte Carlo simulation yields worst-case values for sum charging power and charging terminal quantity caused by overlaps during the peak hours (Fig. 1). From the economic feasibility point of view, the worst-case based design should be avoided; meaning the number of charging terminals, i.e. the EV ports of an ultrafast charging station is to be optimised as well under the consideration of excessive charging queue avoidance.

## Results and Discussion

Based on 10’000 Monte Carlo iterations with input data subjected to distributions as shown in Fig. 2 and Fig. 3, results given in Table 3 were obtained. The station sum load and quantity of EV ports clearly confirm the initial assumptions of overlaps during peak hours, when several vehicles are recharging simultaneously. To meet the worst-case congestions, either medium-voltage grid connection should be considered or buffering and load management techniques applied.

Table 3. Daily power and energy values for charging time 5 min

| | Power at EV input [kW] | | | Transferred energy [kW·h] | | | N° of EV ports | |
|---|---|---|---|---|---|---|---|---|
| EV/day | Per single EV | | Station max | Median | 3Q | Max | 3Q | Max |
| 50 | Median | 214 | 1’421 | 907 | 942 | 1’113 | 1 | 4 |
| 100 | 3Q | 284 | 1’733 | 1’851 | 1’901 | 2’220 | 1 | 6 |
| 200 | Max | 697 | 2’218 | 3’652 | 3’729 | 4’061 | 2 | 8 |

The simulation results without load management (charging power and EV port limitation) are shown in Table 4, where $E_{st}$ symbolises buffer capacity. It is already visible, that prospective grid burden has become smaller than at direct EV grid connection, i.e. in case without decoupling (Table 3). Load shifting requires more buffer capacity due to augmented nighttime accumulation.

Table 4. Grid and storage parameters for load leveling and shifting without load management

| EV/day | Load levelling based on 1 h moving average | | | Load shifting | | |
|---|---|---|---|---|---|---|
| | $P_{gr}$ [kW] | $P_{st}$ [kW] | $E_{st}$ [kW·h] | $P_{gr}$ [kW] | $P_{st}$ [kW] | $E_{st}$ [kW·h] |
| 50 | 112 | 730 | 144 | 84 | 761 | 639 |
| 100 | 196 | 733 | 218 | 157 | 874 | 1155 |
| 200 | 426 | 1381 | 334 | 322 | 1637 | 2281 |

Moreover, the buffering eliminates the need for medium voltage grid connection, as the station's input power can now be supplied from the low voltage side if the transformer substation and the designed charging station are adjacent to each other. The fuse and cable guidelines for a standardised European 0.4 kV three-phase grid connection are given in Table 5.

Table 5. Fuse and cable values for a buffered 0.4 kV low voltage three-phase grid connection

| EV/day | Load levelling based on 1 h moving average | | | Load shifting | | |
|---|---|---|---|---|---|---|
| | Fuse setting | Phase conductor cross-section | | Fuse setting | Phase conductor cross-section | |
| | | Copper | Aluminium | | Copper | Aluminium |
| 50 | 200 A | 70 mm² | 120 mm² | 125 A | 35 mm² | 50 mm² |
| 100 | 320 A | 150 mm² | 240 mm² | 250 A | 120 mm² | 150 mm² |
| 200 | 630 A | 2x185 mm² | 2x240 mm² | 500 A | 2x120 mm² | 2x185 mm² |

The graphical representations of EV charging station load for 50 EV/day and 200 EV/day are shown in Fig. 5 and Fig. 6, respectively. The peak charging power values represent the congestion cases when a station is supposed to serve multiple vehicles simultaneously, i.e. the vehicles arrive to a station at intervals shorter than the charging time itself. These peaks are effectively filtered out by the levelling strategy. The advantage of load shifting is that the buffered station draws most of its energy during nighttime, when the grid is less loaded and electricity prices lower.

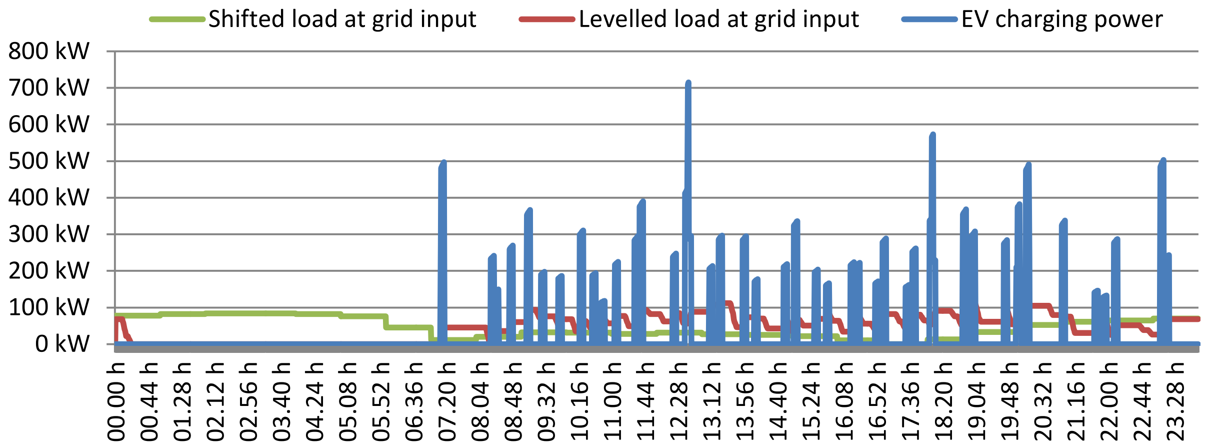


Fig. 5. Buffering example for 50 EV/day without load-side management

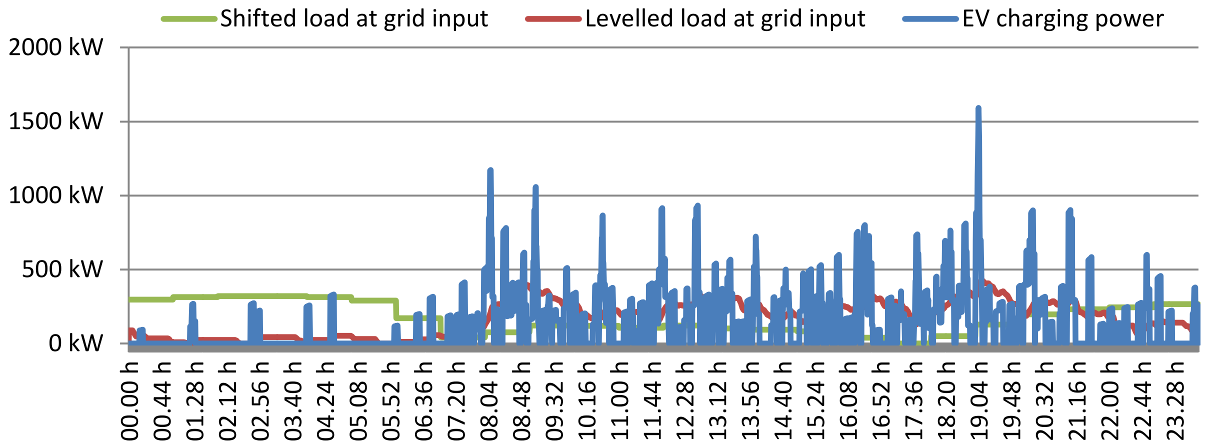


Fig. 6. Buffering example for 200 EV/day without load-side management

The load-side management with charging power limitation causes prolonged charging times at higher EV battery capacities and sequently the probability of overlaps. If EV connection ports are limited in number as well, waiting queues form at the station. So a compromise must be found between hardware optimisation and the driver comfort, otherwise the advantages of ultrafast charging would be cancelled by additional time spent in queues. For instance, if the EV charging power is limited to the 3rd quartile value 284 kW acquired during simulations (Table 3) and an EV connection port number smaller than simulations' maximum is chosen, waiting queues characterised in Table 6 emerge.

Table 6. Prospective waiting queues at charging power limited to 3rd quartile 284 kW

| EV/day | N° of EV ports | | Waiting time at proposed N° of EV outputs [min] | | |
|---|---|---|---|---|---|
| | Simulations' max | Proposed | Median | 3rd quartile | Max |
| 50 | 4 | 1 | 4.0 | 5.6 | 21.9 |
| 100 | 6 | 2 | 0.5 | 2.5 | 11.3 |
| 200 | 8 | 3 | 0.0 | 1.0 | 10.4 |

The buffered energies can be considered unaltered as compared to non-managed case, though actually they decrease negligibly due to smaller losses at smaller energy transfer rates. By combining the managed power data (Table 7) with previously obtained values for power and energy (Table 4), the buffer-scheduling optimised parameters result (Table 7).

Table 7. Connection powers and buffer capacities with load-side management and scheduling

| EV/day | EV ports | Grid connection [kW] | | Buffer connection [kW] | Buffer capacity [kW·h] | |
|---|---|---|---|---|---|---|
| | | Levelling | Shifting | | Levelling | Shifting |
| 50 | 1 · 284 kW | 112 | 84 | 315 | 144 | 639 |
| 100 | 2 · 284 kW | 196 | 157 | 630 | 218 | 1155 |
| 200 | 3 · 284 kW | 426 | 322 | 945 | 334 | 2281 |

With scheduling, the charging station's output (Fig. 7) shows fewer fluctuations than at non-managed case (Fig. 6). The maximum load is reduced by ~45 % and the gaps between connections are reduced to minimum, meaning that, during daytime, the station is busy with great probability.

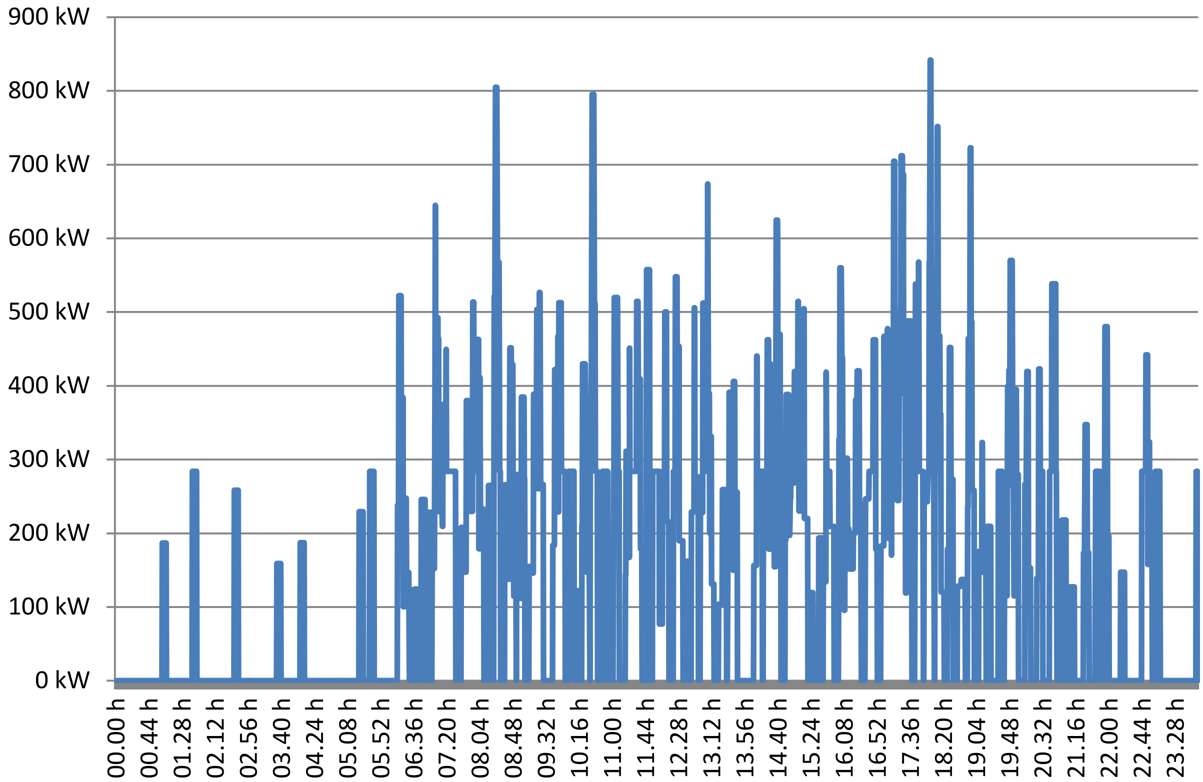


Fig. 7. Load curve for 200 EV/day with scheduling and charging power limitation

A prospective ultrafast charging station should be based on a modular concept, where several units like depicted in Fig. 4 can be paralleled to match the actual utilisation of the station. Thus, for instance, a single unit can be designed for recharging 50 EV/day, if the utilisation augments to 200 EV/day, the station can be extended by adding three similar units (Fig. 8).

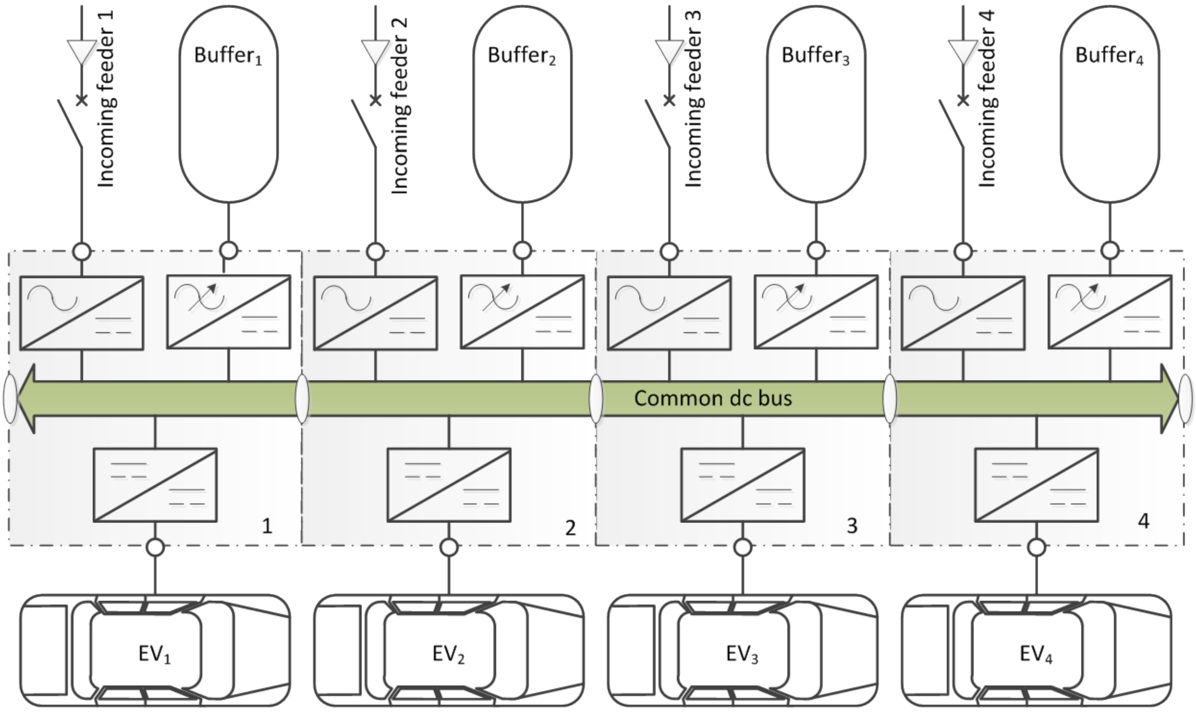


Fig. 8. A buffered ultrafast charging station with four EV ports based on modular architecture

With 284 kW charging power and the unaltered EV average energy consumption of 15 kW·h / 100 km, the autonomy flowrate is improved even at an energy transmission efficiency of 85 %, the latter value defined mostly by the power dissipation over EV battery's internal resistance and efforts for forced cooling. Thus, the autonomy flowrate can reach 22 km/min in comparison to CHAdeMO-provided 4 km/min (Table 2).

In Table 8, the basic energetic data of different storage units suitable for buffering are given together with a load shifting and scheduling example for 200 EV/day. Based on the results presented in Table 3, the average energy sold each day amounts to about 3'650 kWh, while the storage system needs to be able to store approximately 2'300 kWh (Table 7 and Table 4). Given the current low price of electricity, the investments for civil infrastructure, electric converters and storage system will have the biggest impact on the total cost of ownership (TCO), followed by maintenance and operational costs. The external expenses on premises, construction and connection to the existing utility grid are likely to be more than that of the buffered station itself.

Table 8. Comparison of energetic characteristics of storage media[11,12,13,14]

| Technology | Energy density [W·h/l] | Power density [W/l] | 200 EV/day $V$ [m³] | Lifetime [cycles] | Roundtrip efficiency |
|---|---|---|---|---|---|
| Lead-acid | 74 | 250 | 31 | $\sim 10^3$ | 80 % |
| Li-ion high-energy | 630 | 650 | 4 | $\sim 10^4$ | 95 % |
| Li-ion high-power | 140 | 1'400 | 16 | $\sim 10^4$ | 90 % |
| Supercapacitor | 7.6 | 7'400 | 300 | $\sim 10^5$ | 90 % |
| Flywheel | 18 | 1'300 | 127 | $\sim 10^6$ | 85 % |
| Compressed air (CAES) | 24 | 24 | 95 | $\sim 10^5$ | 60 % |
| Redox flow batteries (RFB) | 30 | 80 | 76 | $\sim 10^4$ | 73 % |

Based on current market prices scale, several technologies (lead-acid, CAES and RFB) require less than $2M of investment for the storage system[11]. Lithium-ion batteries are significantly more expensive (at least $5M would be required for both high-energy and high-power batteries) but remain cheaper than supercapacitors and flywheels which would represent an investment of $10M or more.

Although the other important economy descriptor, return on investment (ROI), depends on a large number of factors, like number of years of operation considered, storage system technologies, infrastructural costs, price charged to the customers, etc., it appears that a double digit can be achieved in less than 10 years by choosing the most cost effective solutions. Considering the current state of risk and technological readiness of redox-flow based technologies, CAES and lead-acid batteries appear much more attractive. In fact if the "second-life batteries" market is considered, substantial benefits can be made thanks to the very low acquisition cost those batteries have.

A more thorough analysis has to be performed in order to establish the optimal parameters of this analysis (in particular the price to be charged to the customer has to be determined through survey) but the preliminary results show that there would be a business case and that the limitation is currently situation on the EV side (number of EVs in circulation too low, on-board battery and charging system forbidding ultra-fast charging) rather than on the charging station one.

**Acknowledgements**
The authors would like to thank The Competence Centre Energy and Mobility (CCEM) as well as the Swisselectric Research for their continuous support to the EPFL industrial electronics laboratory research team in the field of EV infrastructure related studies.

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